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Combined active and reactive power control in an operation of a wind farm

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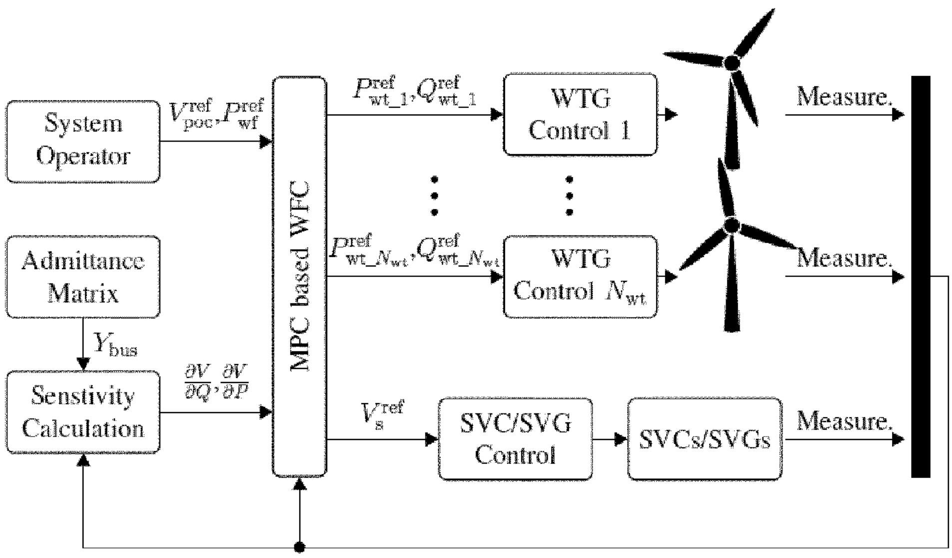

FIG. 2

(57) **Abstract:** The present disclosure relates to a method and system for controlling an operation of a wind farm connected to a grid, the wind farm comprising a plurality of wind turbines, each wind turbine having a local controller, the method comprising the steps of: minimizing a central voltage deviation in a point of connection between the grid and the wind farm compared to a reference voltage provided by the grid; and/or minimizing local voltage deviations compared to local bus reference voltages for each connection to the wind turbines, by: calculating sensitivity coefficients for the wind turbines; and regulating local power references comprising an active power reference and a reactive power reference to each of the local controllers based on the calculated sensitivity coefficients.

WO 2018/115431 A1

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Combined active and reactive power control in an operation of a wind farm

The present disclosure relates to a method and system for controlling an operation of a wind farm having a number of wind turbines by coordination of active and reactive power control.

Background of invention

Wind power is the fastest growing Renewable Energy Resource (RES). With the increasing penetration level, the variability and uncertainty of wind power have brought new technical challenges to the power system operation. The technical requirements for wind power integration are more stringent. These requirements include active power regulation capability and voltage operating range at the Point of Connection (POC) to the grid in which the wind farm operates.

For active power control, by coordination of individual Wind Turbine Generators (WTGs), the wind farm shall track the power reference from the grid provided by the system operator. The reduction of fatigue loads experienced by WTGs to extend their service may be another control objective. For reactive power control, besides WTGs, other fast Var regulation devices, such as Static Var Compensators (SVCs) and Static Var Generators (SVGs) may be used to regulate the voltage at the POC.

One problem with conventional systems for operating wind farms is that they provide limited voltage controllability and stability of the wind farm. In particular, when a bus voltage, either a local bus somewhere in the wind farm or the POC to the grid, violates its constraint, it will be urgent to regulate the violated bus voltage back in order to avoid potential cascading failures in the system.

Summary of invention

Conventionally, the active and reactive powers are controlled separately to fulfill the requirements. In modern wind farms, the WTGs are connected by Medium Voltage (MV) feeders which may be relatively long and their X/R ratio (ratio of reactance to resistance) is typically low ($X/R \leq 1$). The inventors of the presently disclosed method and system have realized that, since, besides the reactive power, the active power change has a significant impact on the voltage variation, the active power can be controlled in coordination with the reactive power to improve controllability and stability of the wind farm. Therefore, in the presently disclosed method system for controlling an operation of a wind farm, active power control is involved to stabilize the voltages by adjusting the active power references of WTGs. Compared to only reactive power compensation, the voltages are better controlled and the recovery of the violated voltage is faster.

The present disclosure relates to, in a first embodiment, a method for controlling an operation of a wind farm connected to a grid, the wind farm comprising a plurality of wind turbines, each wind turbine having a local controller, the method comprising the steps of:

- minimizing a central voltage deviation in a point of connection between the grid and the wind farm compared to a reference voltage provided by the grid; and/or
- minimizing local voltage deviations compared to local bus reference voltages for each connection to the wind turbines,

by:

- calculating sensitivity coefficients for the wind turbines; and
- regulating local power references comprising an active power reference and a reactive power reference to each of the local controllers based on the calculated sensitivity coefficients.

The proposed method for controlling an operation of a wind farm is suitable for real-time control of large-scale wind farms. By including sensitivity coefficients from the wind turbines and regulating local power references comprising an active power reference and a reactive power reference to the local controllers the voltage controllability and stability of the wind farm may be significantly improved.

Moreover, since the Var capability of WTGs may be constrained by the operating limits of the converters its range may be dependent on the terminal voltage and active power production. When WTGs operate close to their full load, the Var capacity will typically decrease significantly, which implies the decrease of voltage support capability. Therefore, by optimally adjusting the active power references to the WTGs, the Var capacity of the whole wind farm can be optimized to deal with potential voltage disturbances.

The active power references and reactive power references may be coordinated for minimizing the central and local voltage deviations. The sensitivity coefficients may be voltage sensitivity coefficients. The voltage sensitivity coefficients may indicate expected voltage changes as a result of the change of active power and reactive power at corresponding connections to the wind turbines. The proposed combined scheme thereby efficiently coordinates the power regulation devices, which may significantly improve the voltage controllability and stability of the wind farm.

Preferably the wind turbines are modelled by a prediction model. The dynamic responses of the controlled devices, which may include WTGs and SVCs/SVGs, typically have different time constants. The presently disclosed method and system for controlling a wind farm may be based on a Model Predictive Control (MPC). The MPC may use a receding horizon principle to solve a finite-horizon optimal control problem over a fixed interval of time. The inventors have realized that this makes it particularly suitable for modelling the WTGs and formulating an MPC problem, by solving which will generate regulation commands for the WTGs.

The method and system may comprise two operation modes. In a normal mode, voltage deviations are minimized as described above and may further take into account further objectives such as minimizing fatigue loads of WTGs. In an emergency mode, wherein at least one of the central voltage deviation or local voltage deviations exceeds a threshold, some control objectives may be compromised. In the emergency mode, the regulation of the local power references to the local controllers are based on the voltage sensitivity coefficients, and may be specifically targeting a correction of the voltage deviation that exceeds the threshold.

The present disclosure further relates to a computer-implemented windfarm operation system comprising at least one hardware processor and at least one storage device storing instructions, wherein the instructions, when executed by the at least one hardware processor, causes the windfarm operation system to perform any embodiment of the presently disclosed method. The system may therefore be configured to perform the method for controlling an operation of a wind farm. The system may be adapted to be connected to a wind farm comprising a plurality of wind turbines. Moreover, the system may further comprise communication units in the (local) wind turbines configured to communicate measurements, such as output voltages, for Static Var Compensators and/or Static Var Generators of individual wind turbines.

Preferably in such a system there is at least one central processing unit configured to perform the steps of the method. The disclosure further relates to a non-transitive, computer-readable storage device for storing instructions that, when executed by a processor, performs the method.

Description of drawings

Fig. 1 shows an example of a configuration of a wind farm.

Fig. 2 shows a wind farm control structure.

Fig. 3 shows a model of a wind turbine having a local controller.

Fig. 4 shows an example of a wind farm being integrated into an IEEE 14 bus system.

Fig. 5 shows a first example of power production and power reference tracking for a conventional algorithm and the presently disclosed method.

Fig. 6 shows voltage deviations on two buses during operation for the first example.

Fig. 7 shows the Var output of a Static Var Generator for a conventional controller and the presently disclosed controller.

Fig. 8 shows a second example of power production and power reference tracking for a conventional algorithm and the presently disclosed method.

Fig. 9 shows the total Var capacity and Var capacity ranges for a conventional algorithm and the presently disclosed method.

Fig. 10 shows voltage deviations on two buses during operation for the second example.

Detailed description of the invention

The present disclosure relates to a method and system for controlling an operation of a wind farm connected to a grid. The wind farm comprises a plurality of wind turbines, wherein each wind turbine has a local controller. In a first aspect the method minimizes a central voltage deviation in a point of connection between the grid and the wind farm compared to a reference voltage provided by the grid; and/or minimizes local voltage deviations compared to local bus reference voltages, preferably for each connection to the wind turbines by coordinating the active and reactive power control to the local controllers. The method may be adapted to calculate voltage sensitivity coefficients for the wind turbines, said voltage sensitivity coefficients, possibly comprising an active power part and a reactive power part. By controlling local power references comprising an active power reference and a reactive power reference to the local controllers, the method may improve voltage stability and voltage recovery on one or several buses.

Preferably the local power reference control is based on the calculated voltage sensitivity coefficients.

By involving both the reactive and the active power control the bus voltages can be more efficiently stabilized. Compared to only reactive power compensation, the voltages are better controlled and the recovery of the violated voltage is faster.

In one embodiment the reactive and active power control are coordinated to improve, preferably maximize, the Var capacity of the system. Var shortage is a frequent reason for failure in the conventional controlled wind farms. In particular when the wind farm operates close to its full load, the Var capacity will significantly decrease, which implies the decrease of voltage support capability. By maximizing the fast Var reserve potential, disturbances can be more efficiently handled.

The controller may be arranged to operate in two modes: normal mode and emergency mode. The normal mode may comprise the steps of minimizing the central and local voltage deviations by: calculating voltage sensitivity coefficients for the wind turbines, said voltage sensitivity coefficients and regulating local power references comprising an active power reference and a reactive power reference to each of the local controllers based on the calculated voltage sensitivity coefficients. In the emergency mode, wherein at least one of the central voltage deviation or local voltage deviations exceeds a threshold, the controller may be further arranged to correct the voltage deviation that exceeds the threshold by regulating local power references to each of the local controllers based on the active power part and the reactive power part of the calculated voltage sensitivity coefficients. The normal mode may comprise control objectives for tracking the power reference of the wind farm, and/or minimizing fatigue loads, and/or maximizing the fast Var capacity, whereas the emergency mode only has one control objective: the regulation of the violated voltages back to their limits.

The wind turbines in the presently disclosed controller and control method may be modelled by a prediction model. The dynamic responses of the controlled devices, including WTGs and SVCs/SVGs, have different time constants. Therefore the method/system may be based on a Model Predictive Control (MPC). The MPC approach may use a receding horizon principle to solve a finite-horizon optimal control problem over a fixed interval of time. The prediction model may further comprise a variable speed-pitch controlled wind turbine model comprising P and Q control loops.

Fig. 1 illustrates a typical configuration of a wind farm. The buses within the wind farm include a bus at the POC, a bus at the collection point (located at medium voltage (MV) side of the main substation transformer) and buses of WTGs. One embodiment of the proposed structure according to the presently disclosed wind farm controller is shown in fig. 2. The active power and voltage references at the POC of the wind farm, P_{wf}^{ref} and V_{poc}^{ref} , are decided by the system operator and delivered to the WFC. The measurements of individual WTGs and SVCs/SVGs are sent directly to the WFC. Based on the calculated voltage sensitivities ($\frac{\partial V}{\partial P}$, $\frac{\partial V}{\partial Q}$) and the prediction models of WTGs and SVCs/SVGs, the MPC problem is formulated. By solving the MPC problem, the regulation commands for all WTGs (P_{wt}^{ref} , Q_{wt}^{ref}) and SVCs/SVGs (V_s^{ref}) are determined and delivered to their local controllers.

Modeling and operation

Fig. 3 shows an example of a model of one WTG. A WTG may be considered as an actuator, which follows the assigned power commands P_{wt}^{ref} and Q_{wt}^{ref} . In the example the P and Q control loops are decoupled.

P loop: Since the sampling time of the WFC is normally in seconds, the fast dynamics of the generator and pitch actuator are neglected. The generator efficiency μ is compensated in the WTG controller. Accordingly, the power production P_{wt} is derived approximately by $P_{wt} \approx P_{wt}^{ref}$. The nonlinear model can be linearized around the operating points.

$$\dot{x}_{\mathrm{wt}}^{p} = \boldsymbol{A}_{\mathbf{wt}}^{\boldsymbol{p}} x_{\mathrm{wt}}^{p} + \boldsymbol{B}_{\mathbf{wt}}^{\boldsymbol{p}} P_{\mathrm{wt}}^{\mathrm{ref}} + \boldsymbol{E}_{\mathbf{wt}}^{\boldsymbol{p}}$$

where x_{wt}^{p} refers to the state vector defined by $x_{wt}^{p} \triangleq [0, \omega_{r,} \omega_f]^{\mathrm{t}}$, 0 is the pitch angle, ω_r and ω_f are the rotor speed and the filtered generator speed ω_g, respectively. The state space matrices are:

$$\boldsymbol{A}_{\mathrm{s}} = \begin{bmatrix} -\frac{1}{\tau_{\mathrm{s}}}(1 + K_{\mathrm{p\_s}}\frac{\partial |V_{\mathrm{s}}|}{\partial Q_{\mathrm{s}}}) & \frac{K_{\mathrm{i\_s}}}{\tau_{\mathrm{s}}} \\ -\frac{\partial |V_{\mathrm{s}}|}{\partial Q_{\mathrm{s}}} & 0 \end{bmatrix}, \boldsymbol{B}_{\mathrm{s}} = \begin{bmatrix} \frac{K_{\mathrm{p\_s}}}{\tau_{\mathrm{s}}} \\ 1 \end{bmatrix},$$

$$\boldsymbol{E}_{\mathrm{s}} = \begin{bmatrix} -\frac{K_{\mathrm{p\_s}}}{\tau_{\mathrm{s}}}\frac{\partial |V_{\mathrm{s}}|}{\partial P_{\mathrm{wt}}} \\ -\frac{\partial |V_{\mathrm{s}}|}{\partial P_{\mathrm{wt}}} \end{bmatrix}, \boldsymbol{F}_{\mathrm{s}} = \begin{bmatrix} -\frac{K_{\mathrm{p\_s}}}{\tau_{\mathrm{s}}}\frac{\partial |V_{\mathrm{s}}|}{\partial Q_{\mathrm{wt}}} \\ -\frac{\partial |V_{\mathrm{s}}|}{\partial Q_{\mathrm{wt}}} \end{bmatrix},$$

$$\boldsymbol{G}_{\mathrm{s}} = \begin{bmatrix} -\frac{K_{\mathrm{p\_s}}\Delta V_{\mathrm{s}}^0}{\tau_{\mathrm{s}}} + \frac{Q_{\mathrm{s}}^0}{\tau_{\mathrm{s}}} \\ -\Delta V_{\mathrm{s}}^0 \end{bmatrix},$$

where η_g is the gearbox ratio, $J_t d \triangleq J_r + \eta_g^2 J_g$ is the equivalent inertia, τ_g is the rotor torque, $P_{wt}^0, \theta^0, \omega_g^0$ and v_w^0 denote the measured power output, pitch angle, generator speed and wind speed at the operating point, respectively.

Q loop: The dynamic behavior of the constant-Q control of WTGs can be described by a first order function. The state space model is

$$\dot{x}_{\mathrm{wt}}^{q} = \boldsymbol{A}_{\mathbf{wt}}^{\boldsymbol{q}} x_{\mathrm{wt}}^{q} + \boldsymbol{B}_{\mathbf{wt}}^{\boldsymbol{q}} Q_{\mathrm{wt}}^{\mathrm{ref}}$$

where x_{wt}^q is the state variable, defined by $x_{wt}^q \triangleq Q_{wt}$. The state matrices are:

$$\boldsymbol{A}_{\mathbf{wt}}^{\boldsymbol{q}} = -\frac{1}{\tau_{\mathrm{q}}},\ \boldsymbol{B}_{\mathbf{wt}}^{\boldsymbol{q}} = \frac{1}{\tau_{\mathrm{q}}}$$

where τ_q is the time constant for the Q loop.

The SVC/SVG may also be dynamically modelled, wherein the dynamics of the constant-Q control loop of SVC/SVG is described by a first order function:

$$Q_{\mathrm{s}} = \frac{1}{1 + s\tau_{\mathrm{s}}} Q_{\mathrm{s}}^{\mathrm{ref}}$$

The voltage at the controlled bus (POC) can be described as:

$$V_s = V_s^0 + \frac{\partial |V_s|}{\partial Q_s} \Delta Q_s + \frac{\partial |V_s|}{\partial P_{wt}} \Delta P_{wt} + \frac{\partial |V_s|}{\partial Q_{wt}} \Delta Q_{wt}.$$

In a further model according to the presently disclosed system, the P, Q loops of WTG and SVC/SVG models can then be merged into a combined model, comprising a number N_{wt} of wind turbines and a number N_s of SVCs/SVGs.

In one embodiment the model may therefore represent a number of wind turbines and SVCs/SVGs, preferably expressed in the form of combined matrix.

Sensitivity calculation

In the step of calculating sensitivity coefficients for the wind turbines, an analytical computation method for calculating the sensitivity coefficients may be used to improve the computation efficiency.

Voltage sensitivity coefficients in the presently disclosed method for controlling an operation of a wind farm may indicate expected voltage changes as a result of the change of active power and reactive power at corresponding connections to the wind turbines. Voltage sensitivity coefficients may be expressed as ($\frac{\partial V}{\partial P}$, $\frac{\partial V}{\partial Q}$).

The sensitivity coefficients may alternatively, or in combination with the voltage sensitivity coefficients, comprise a Var capacity sensitivity part.

Model predictive control problem and optimization

The wind turbines may be modelled by a prediction model. The sampling period of the WFC may be t_s and the prediction period may be t_p. Compared with the time constants of the fast Var devices, t_s is larger, which is normally in seconds. In order to capture the fast dynamics, the sampling period of the prediction may be smaller. Thus, t_s may be further divided into n_s steps. Accordingly, the total number of prediction steps can be calculated by $n_p = (t_p/t_s)n_s$.

The predictive control problem may be expressed such that in a solution the active power references and reactive power references are coordinated for minimizing the central and local voltage deviations.

According to the introduced model comprising a P loop and Q loop, the prediction model may accordingly comprise a variable speed-pitch controlled wind turbine model comprising P and Q control loops. The prediction model may use a sampling time of less than 10 s, preferably less than 5 s, even more preferable less than 1 s, most preferably less than 0.1 s.

In one embodiment a cost function is introduced, which may be used in calculations for optimizing a control objective.

One control objective relates to the deviation between measured voltages of the wind farm and their references (ΔV_{poc}, ΔV_{wt}), wherein the deviation is minimized in the presently disclosed method. ΔV_{poc} and ΔV_{wt} may be affected by active and reactive power injection of SVCs/SVGs and WTGs, which may be calculated by:

$$\begin{aligned}\Delta V_{\mathrm{poc}}(k) &= V_{\mathrm{poc}}^{0} + \frac{\partial|V_{\mathrm{poc}}|}{\partial P_{\mathrm{wt}}}\Delta P_{\mathrm{wt}}(k) + \frac{\partial|V_{\mathrm{poc}}|}{\partial Q_{\mathrm{wt}}}\Delta Q_{\mathrm{wt}}(k)\\ &\quad + \frac{\partial|V_{\mathrm{poc}}|}{\partial Q_{\mathrm{s}}}\Delta Q_{\mathrm{s}}(k) - V_{\mathrm{poc}}^{\mathrm{ref}},\\ \Delta V_{\mathrm{wt}}^{\mathrm{pre}}(k) &= V_{\mathrm{wt}}^{0} + \frac{\partial|V_{\mathrm{wt}}|}{\partial P_{\mathrm{wt}}}\Delta P_{\mathrm{wt}}(k) + \frac{\partial|V_{\mathrm{wt}}|}{\partial Q_{\mathrm{wt}}}\Delta Q_{\mathrm{wt}}(k)\\ &\quad + \frac{\partial|V_{\mathrm{wt}}|}{\partial Q_{\mathrm{s}}}\Delta Q_{\mathrm{s}}(k) - V_{\mathrm{wt}}^{\mathrm{ref}}.\end{aligned}$$

The sum of ΔV_{poc}, ΔV_{wt} for any combination of points on the buses can then be calculated minimized.

A second control objective relates to minimizing fatigue loads of the wind turbines. Therefore, in one embodiment the method further comprises the step of minimizing fatigue loads of the wind turbines. A minimization of central and local voltage deviation are calculated as an optimization of a sum of voltage deviations based on the prediction model. Using this control objective the shaft torque T_s is transferred through the gearbox. Since the gearbox is typically a vulnerable component, the oscillation of T_s may create micro-cracks in the material and lead to component failure. The load alleviation can be realized by reducing the deviation of T_s.

A third control objective relates to maximizing fast dynamic Var support capabilities. One embodiment of the presently disclosed method for controlling an operation of a wind farm further comprises the step of maximizing a Var support capability of the wind farm. The third control objective may be implemented by minimizing Q_s to its middle level of the operating range $Q_s^{mid} = 0.5\,(Q_s^{max} + Q_s^{min})$. In this manner the Var shortage is compensated by the slower Var devices (WTGs) for maintaining the voltage of buses throughout the wind farm. i.e.:

$$\mathrm{Obj3} = \sum_{k=1}^{n_\mathrm{p}} \| \, Q_\mathrm{s}^\mathrm{pre}(k) - Q_\mathrm{s}^\mathrm{mid} \, \|_{W_\mathrm{s}}^2$$

where W_s refers to its weighting factors. Accordingly, the time for recovering a power disturbance of the wind farm is reduced by a maximized Var support.

The prediction model may further comprise a model of additional Var regulation of the wind farm, such as static Var compensation (SVC) and/or static Var generation (SVG). Such a model of additional Var regulation of the wind farm may comprise multiple SVCs and/or SVGs. The step of regulating local power references to each of the local controller may therefore be further based on the model of additional Var regulation of the wind farm.

Normal mode and emergency mode

The above first, second, and third control objectives, corresponding to objectives relating to deviation between measured voltages and reference voltages, fatigue load minimization and fast dynamic Var support capability may be used alone or combined in a normal operation mode. In one embodiment the steps of minimizing the central and local deviations correspond to a normal mode.

In addition to the normal mode, the system may be configured to operate in an emergency mode, in which the only objective is to correct a violated bus voltage. The violated bus voltage may be any bus in the system. In particular correcting the voltage at the POC may be a control objective in this regard. However, in principle a violation in any point may cause cascading failures in the system and should therefore, preferably, be corrected as quickly as possible.

In one embodiment of the presently disclosed method for controlling an operation of a wind farm, the method therefore further comprises the step of, in an emergency mode, wherein at least one of the central voltage deviation or local voltage deviations exceeds a threshold: correcting the voltage deviation that exceeds the threshold by regulating local power references to each of the local controllers based on the calculated voltage sensitivity coefficients. Preferably an active power part and a reactive power part of the local power references are coordinated to correct the voltage violation. Static Var compensation (SVC) and/or static Var generation (SVG) optimization may also be performed based on the voltage sensitivity coefficients. In the emergency mode the system may temporarily be configured to ignore other constraints. In one embodiment the minimization of fatigue loads and maximization of Var support capability are temporarily ignored in the emergency mode. Any suitable threshold may be applied for activating the emergency mode. In one embodiment the threshold for which the emergency mode is used is less than 30% of the reference voltage, preferably less than 20% of the reference voltage, more preferably less than 10% of the reference voltage.

Examples

An example of a wind farm where the presently disclosed method has been implemented includes a wind farm comprising 10x5MW wind turbines. The wind farm is integrated into an IEEE 14 bus system and the connected bus is a Bus 03, which is located at the terminal of the grid as shown in fig. 4.

The results of the presently disclosed method and controller (COM) are compared with the results for the same scenarios using a conventional controller (SEP) where the active and reactive powers are decoupled and controlled separately.

Case Scenario 1

In a first scenario, Case Scenario 1, a low power production scenario over a simulation period of 0-120 seconds is shown. The power production P_{wf} for both controllers (SEP and COM) and the available wind power P_{wf}^{avi} are shown in fig. 5. P_{wf} of both controllers are almost identical and track the specified ramp rate limit with high precision.

The voltages at two representative buses are used to illustrate the voltage condition of the wind farm, including V_{poc} and V_{wt_15}, which is located at wind turbine 15 (WT15), the furthest bus along the feeder. The voltages are within their thresholds and the WFC therefore operates in the normal mode (for COM). V_{poc} of both controllers are regulated close to the reference value V_{poc}^{ref} as can be seen in fig. 6A. However, the voltage deviation with COM is smaller. Also for a sudden change due to a power fluctuation the recovery of V_{poc} to V_{poc}^{ref} is faster. Considering the impact of active power on the voltage, COM shows better voltage controllability.

Fig. 7 shows the Var output of the SVG Q_s for both controllers for Case Scenario 1. In this case $Q_s^{mid} = 0$. Qs of COM is smaller, which indicates that more fast Var capacity is reserved.

Case Scenario 2

In a second scenario, Case Scenario 2, a high power production scenario is shown over a simulation period of 120 seconds (120-240s).

The available wind power P_{wf}^{avi} and P_{wf} are shown in fig. 8. P_{wf} of both controllers are almost identical. Since P_{wf} is high in this scenario, the active power of several WTGs is high, which may significantly affect their Var capacities. By defining

$$Q_{\mathrm{wt}}^{\mathrm{sum}} \triangleq \sum_{i=1}^{N_{\mathrm{wt}}} Q_{\mathrm{wt}}, Q_{\mathrm{wt}}^{\mathrm{s\_min}} \triangleq \sum_{i=1}^{N_{\mathrm{wt}}} Q_{\mathrm{wt}}^{\mathrm{min}}, Q_{\mathrm{wt}}^{\mathrm{s\_max}} \triangleq \sum_{i=1}^{N_{\mathrm{wt}}} Q_{\mathrm{wt}}^{\mathrm{max}}$$

where Q_{wt}^{sum} denotes the total Var production of WTGs, and $Q_{wt}^{s\_min}$ and $Q_{wt}^{s\_max}$ are the lower and upper limits of the total Var capacity of the WTGs, respectively. Their simulation values are shown in fig. 9. It can be observed that the Var capacity range of COM is larger than that of SEP, especially during the periods t_1 = 201.3s – 207.6s and t_2 = 232.2s - 236s. For SEP, due to the decoupled active and reactive power control, Q_{wt}^{min} and Q_{wt}^{max} cannot be predicted. There are sudden decreases of the total Var capacity in t_1 and t_2. Accordingly, the voltage support capability is reduced in these periods. For COM, Q_{wt}^{min} and Q_{wt}^{max} can be predicted based on the predictions of P_{wt} and V_{wt}. The possible Var shortage is considered in the MPC. Therefore, the total Var capacity is kept stable for the whole period for COM.

The voltage results are shown in fig. 10. For SEP, V_{poc} is often beyond its operation limits [0.98 p.u, 1.02 p.u], fig. 10A. Due to the shortage of the Var reserve, V_{wt_15} breaks the protection limit (1.1 p.u.) during t_1 and t_2, which will trigger the protection devices in real operation and may cause a cascading failure (fig. 10B). For COM, the voltage deviations are smaller. In the simulation V_{poc} is always regulated within its limit. In the simulation V_{wt_15} is never beyond the protection limit.

Further details of the invention

The invention will now be described in further detail with reference to the following items:

1. A method for controlling an operation of a wind farm connected to a grid, the wind farm comprising a plurality of wind turbines, each wind turbine having a local controller, the method comprising the steps of:
   - minimizing a central voltage deviation in a point of connection between the grid and the wind farm compared to a reference voltage provided by the grid; and/or
   - minimizing local voltage deviations compared to local bus reference voltages for each connection to the wind turbines,

   by:
   - calculating sensitivity coefficients for the wind turbines; and
   - regulating local power references comprising an active power reference and a reactive power reference to each of the local controllers based on the calculated sensitivity coefficients.

2. The method according to any of the preceding items, wherein the sensitivity coefficients comprise an active power part and a reactive power part.

3. The method according to any of the preceding items, wherein the active power references and reactive power references are coordinated for minimizing the central and local voltage deviations.

4. The method according to any of the preceding items, wherein the sensitivity coefficients are voltage sensitivity coefficients.

5. The method according to item 4, wherein the voltage sensitivity coefficients indicate expected voltage changes as a result of the change of active power and reactive power at corresponding connections to the wind turbines.

6. The method according to item 1-2, wherein the sensitivity coefficients are Var capacity sensitivity coefficients.

7. The method according to any of the preceding items, wherein the wind turbines are modelled by a prediction model.

8. The method according to item 7, wherein the prediction model comprises a variable speed-pitch controlled wind turbine model comprising P and Q control loops.

9. The method according to any of items 7-8, wherein the prediction model has a sampling time of less than 10 s, preferably less than 5 s, even more preferable less than 1 s, most preferably less than 0.1 s.

10. The method according to any of items 7-9, wherein the prediction model further comprises a model of additional Var regulation of the wind farm, such as static Var compensation (SVC) and/or static Var generation (SVG).

11. The method according to item 10, wherein the model of additional Var regulation of the wind farm comprises multiple SVCs and/or SVGs.

12. The method according to item 10-11, wherein the step of regulating local power references to each of the local controller is further based on the model of additional Var regulation of the wind farm.

13. The method according to any of items 7-12, wherein the minimization of central and local voltage deviation are calculated as an optimization of a sum of voltage deviations based on the prediction model.

14. The method according to any of items 7-13, further comprising the step of minimizing fatigue loads of the wind turbines.

15. The method according to any of items 7-14, further comprising the step of maximizing a Var support capability of the wind farm.

16. The method according to item 15, wherein a time for recovering a power disturbance of the wind farm is reduced by the maximized Var support.

17. The method according to any of the preceding items, wherein the step of minimizing the central and local voltage deviations correspond to a normal mode, the method further comprising the step of, in an emergency mode, wherein at least one of the central voltage deviation or local voltage deviations exceeds a threshold: correcting the voltage deviation that exceeds the threshold by regulating local power references to each of the local controllers based on the calculated sensitivity coefficients.

18. The method according to item 17, wherein the voltage deviation is corrected by using a static Var compensation (SVC) and/or static Var generation (SVG) optimized based on the sensitivity coefficients.

19. The method according to any of items 17-18, wherein the minimization of fatigue loads and maximization of Var support capability are temporarily ignored in the emergency mode.

20. The method according to any of items 17-19, wherein the threshold is less than 30% of the reference voltage, preferably less than 20% of the reference voltage, more preferably less than 10% of the reference voltage.

21. The method according to any of the preceding items, wherein the operation is substantially in real-time.

22. A system configured to perform the method according to any of items 1-21.

23. A non-transitive, computer-readable storage device for storing instructions that, when executed by a processor, performs the method according to any of items 1-21.

24. A windfarm comprising a plurality of wind turbines and a processing unit configured to execute the method according to any of items 1-21.

Claims

1. A method for controlling an operation of a wind farm connected to a grid, the wind farm comprising a plurality of wind turbines, each wind turbine having a local controller, the method comprising the steps of:
   - minimizing a central voltage deviation in a point of connection between the grid and the wind farm compared to a reference voltage provided by the grid; and/or
   - minimizing local voltage deviations compared to local bus reference voltages for each connection to the wind turbines,

   by:
   - calculating sensitivity coefficients for the wind turbines; and
   - regulating local power references comprising an active power reference and a reactive power reference to each of the local controllers based on the calculated sensitivity coefficients.

2. The method according to any of the preceding claims, wherein the sensitivity coefficients comprise an active power part and a reactive power part.

3. The method according to any of the preceding claims, wherein the active power references and reactive power references are coordinated for minimizing the central and local voltage deviations.

4. The method according to any of the preceding claims, wherein the sensitivity coefficients are voltage sensitivity coefficients.

5. The method according to claim 4, wherein the voltage sensitivity coefficients indicate expected voltage changes as a result of the change of active power and reactive power at corresponding connections to the wind turbines.

6. The method according to claim 1-2, wherein the sensitivity coefficients are Var capacity sensitivity coefficients.

7. The method according to any of the preceding claims, wherein the wind turbines are modelled by a prediction model.

8. The method according to claim 7, further comprising the step of minimizing fatigue loads of the wind turbines.

9. The method according to any of claims 7-8, further comprising the step of maximizing a Var support capability of the wind farm.

10. The method according to any of the preceding claims, wherein the step of minimizing the central and local voltage deviations correspond to a normal mode, the method further comprising the step of, in an emergency mode, wherein at least one of the central voltage deviation or local voltage deviations exceeds a threshold: correcting the voltage deviation that exceeds the threshold by regulating local power references to each of the local controllers based on the calculated sensitivity coefficients.

11. The method according to claim 10, wherein the voltage deviation is corrected by using a static Var compensation (SVC) and/or static Var generation (SVG) optimized based on the sensitivity coefficients.

12. The method according to any of claims 10-11, wherein the minimization of fatigue loads and maximization of Var support capability are temporarily ignored in the emergency mode.

13. A computer-implemented windfarm operation system comprising at least one hardware processor and at least one storage device storing instructions, wherein the instructions, when executed by the at least one hardware processor, causes the windfarm operation system to perform the method according to any of claims 1-12.

14. The computer-implemented windfarm operation system according to claim 12, wherein the system is adapted to be connected to a wind farm comprising a plurality of wind turbines.

15. The computer-implemented windfarm operation system according to claim 14, further comprising communication units in the wind turbines configured to communicate measurements, such as output voltages, for Static Var Compensators and/or Static Var Generators of individual wind turbines.

16. A non-transitive, computer-readable storage device for storing instructions that, when executed by a processor, performs the method according to any of claims 1-12.

17. A windfarm comprising a plurality of wind turbines and a processing unit configured to execute the method according to any of claims 1-12.

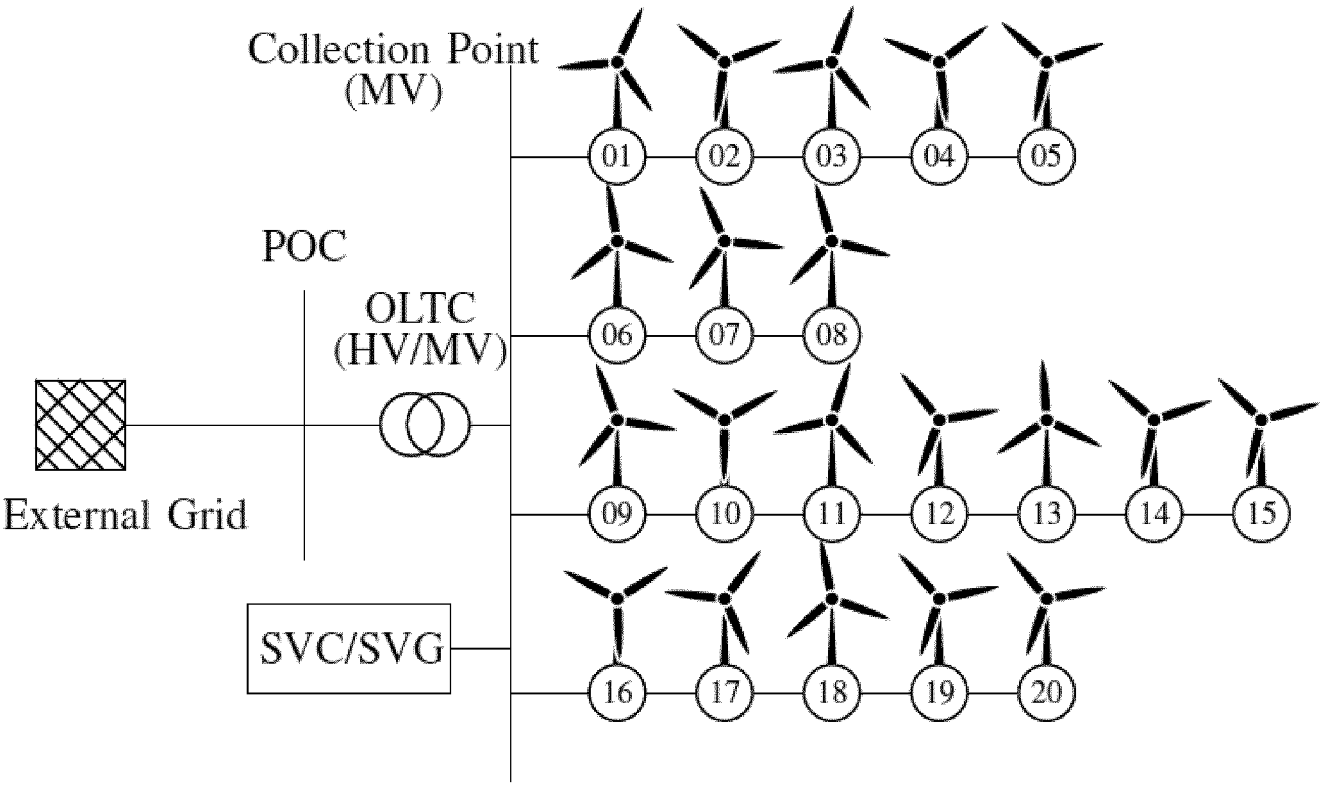

Collection Point
(MV)
POC
OLTC
(HV/MV)
External Grid
SVC/SVG
01
02
03
04
05
06
07
08
09
10
11
12
13
14
15
16
17
18
19
20

FIG. 1

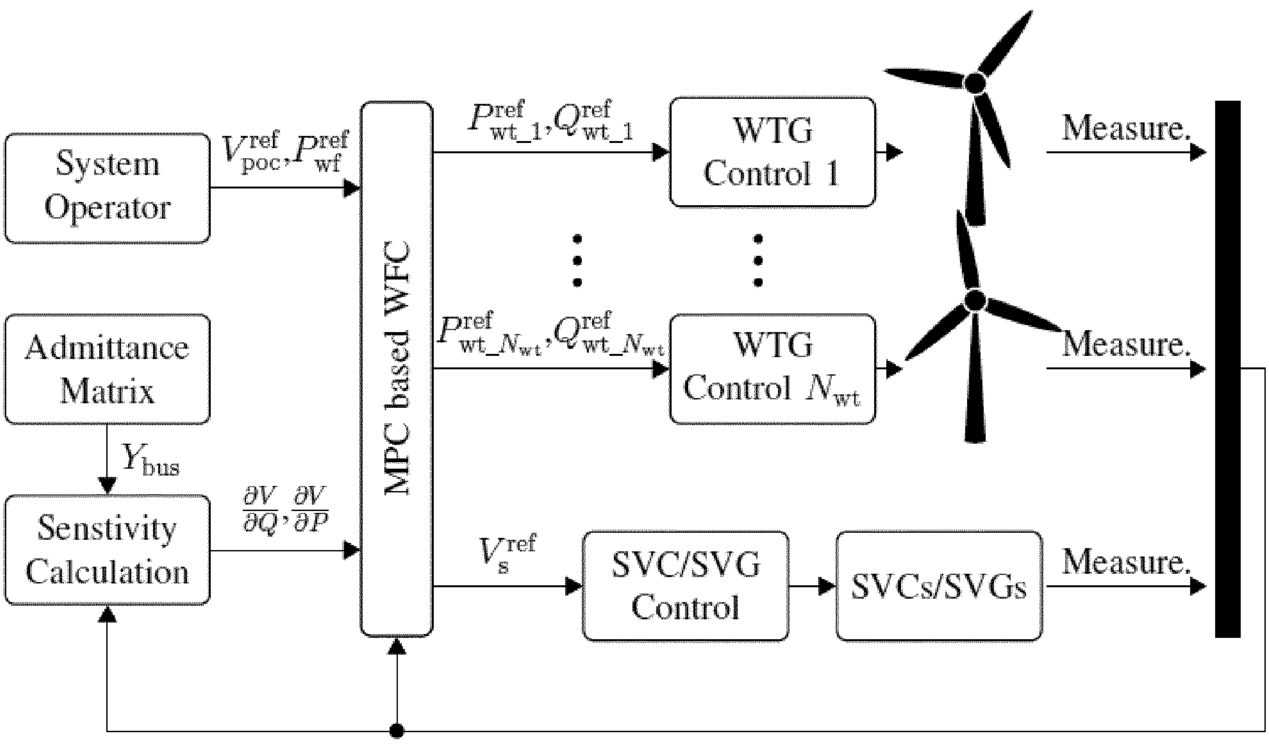
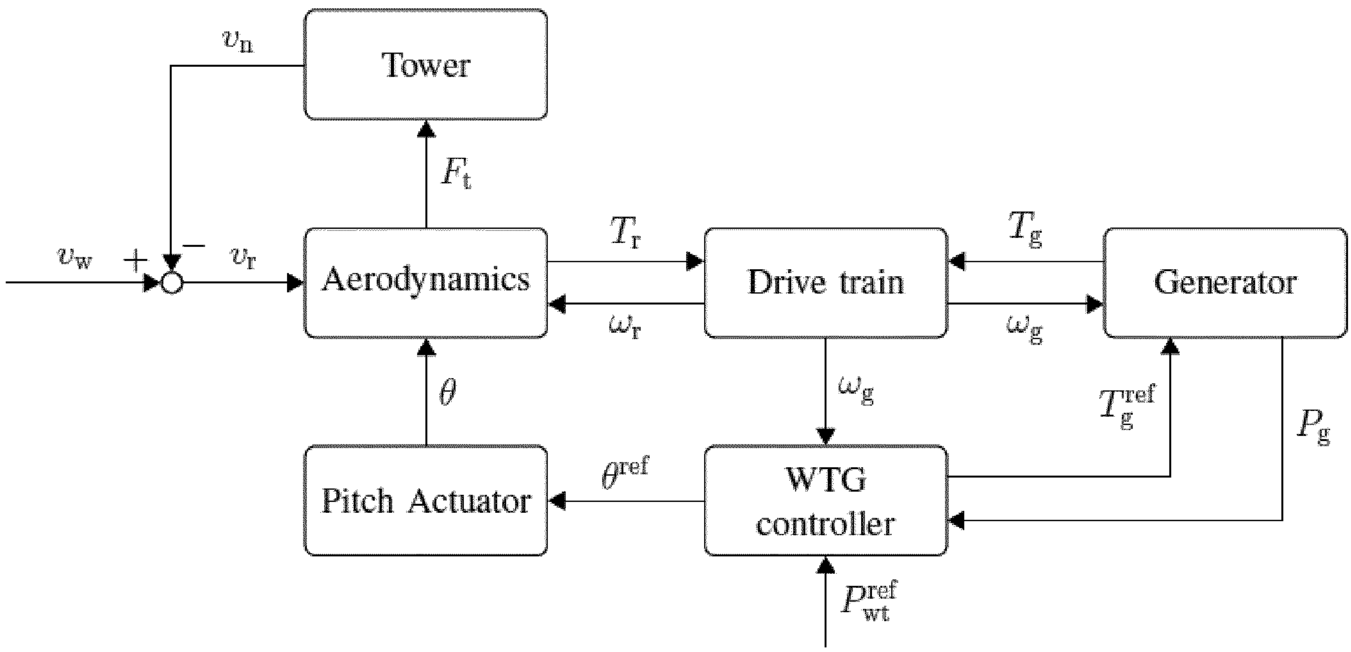
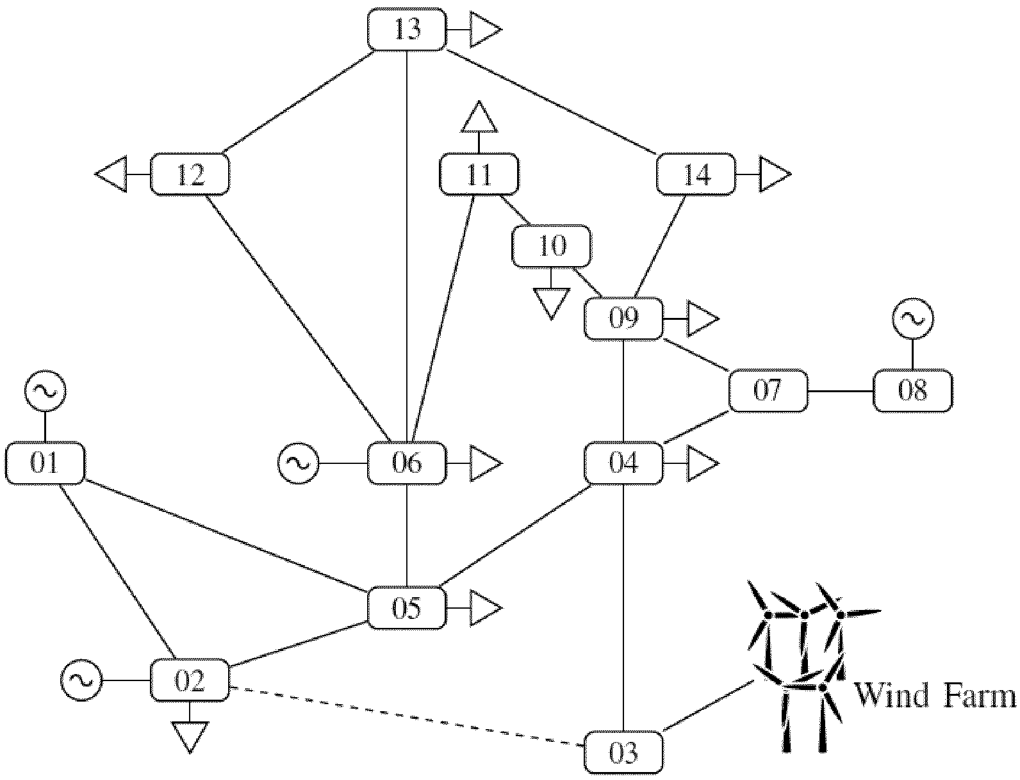

System
Operator
$V_{\mathrm{poc}}^{\mathrm{ref}}, P_{\mathrm{wf}}^{\mathrm{ref}}$
Admittance
Matrix
Y_{bus}
Senstivity
Calculation
$\frac{\partial V}{\partial Q}, \frac{\partial V}{\partial P}$
MPC based WFC
$P_{\mathrm{wt\_1}}^{\mathrm{ref}}, Q_{\mathrm{wt\_1}}^{\mathrm{ref}}$
WTG
Control 1
$P_{\mathrm{wt\_}N_{\mathrm{wt}}}^{\mathrm{ref}}, Q_{\mathrm{wt\_}N_{\mathrm{wt}}}^{\mathrm{ref}}$
WTG
Control N_{wt}
$V_{\mathrm{s}}^{\mathrm{ref}}$
SVC/SVG
Control
SVCs/SVGs
Measure.
Measure.
Measure.

FIG. 2



Tower
v_n
F_t
v_w
+
−
v_r
Aerodynamics
T_r
ω_r
Drive train
T_g
ω_g
Generator
θ
ω_g
T_g^{ref}
P_g
Pitch Actuator
θ^{ref}
WTG controller
P_{wt}^{ref}

FIG. 3



13
12
11
14
10
09
07
08
01
06
04
05
02
03
Wind Farm

FIG. 4

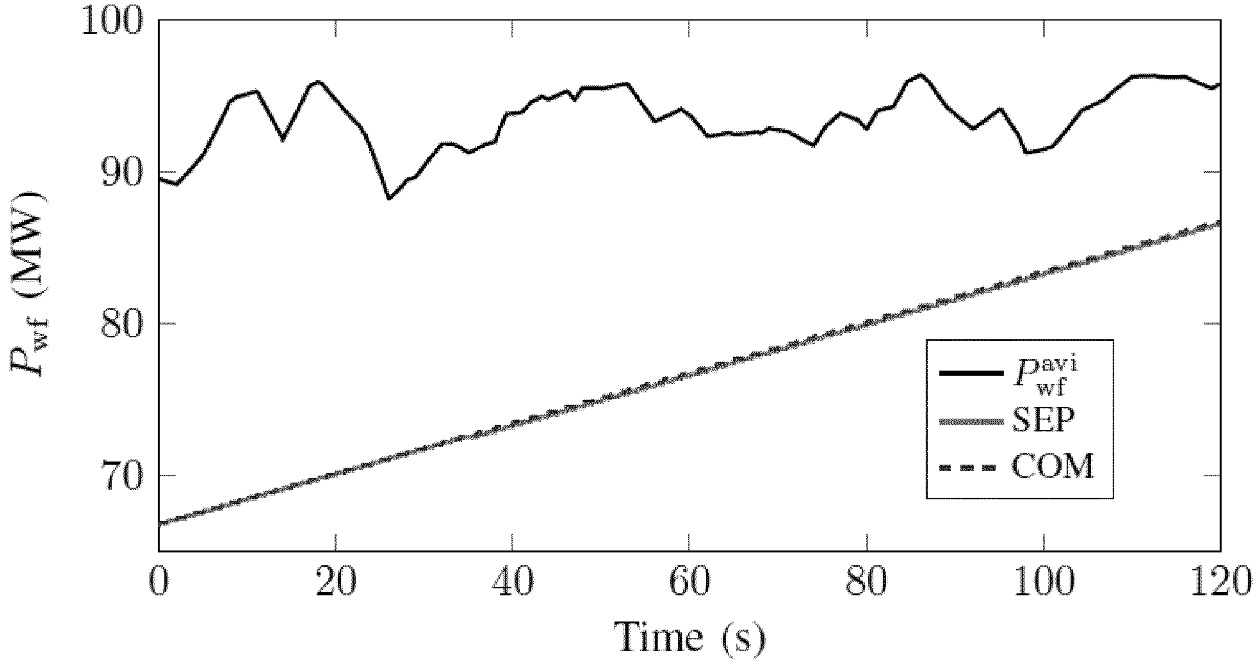

100
90
80
70
P_{wf} (MW)
0
20
40
60
80
100
120
Time (s)
P_{wf}^{avi}
SEP
COM

FIG. 5

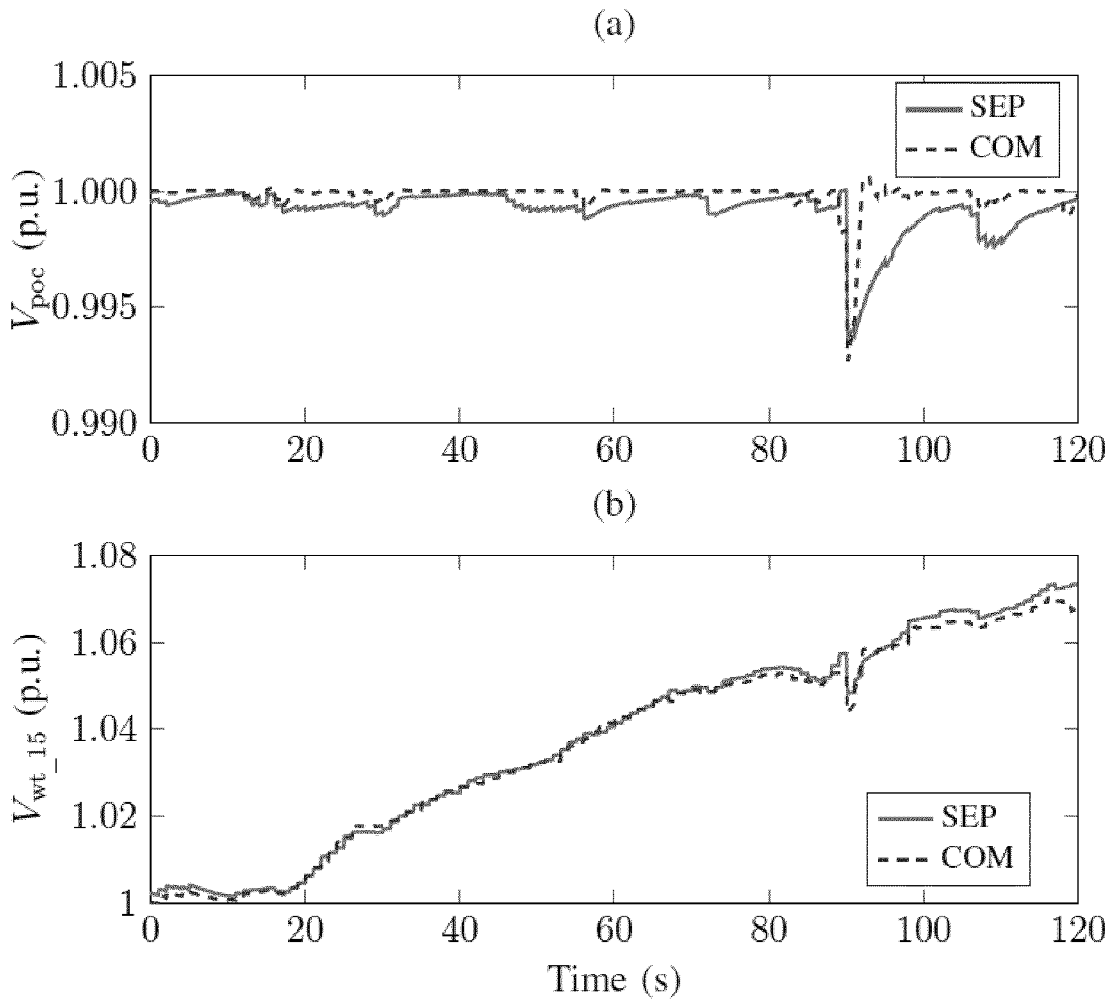

(a)
1.005
1.000
0.995
0.990
V_{poc} (p.u.)
SEP
COM
0
20
40
60
80
100
120
(b)
1.08
1.06
1.04
1.02
1
V_{wt_15} (p.u.)
SEP
COM
0
20
40
60
80
100
120
Time (s)

FIG. 6

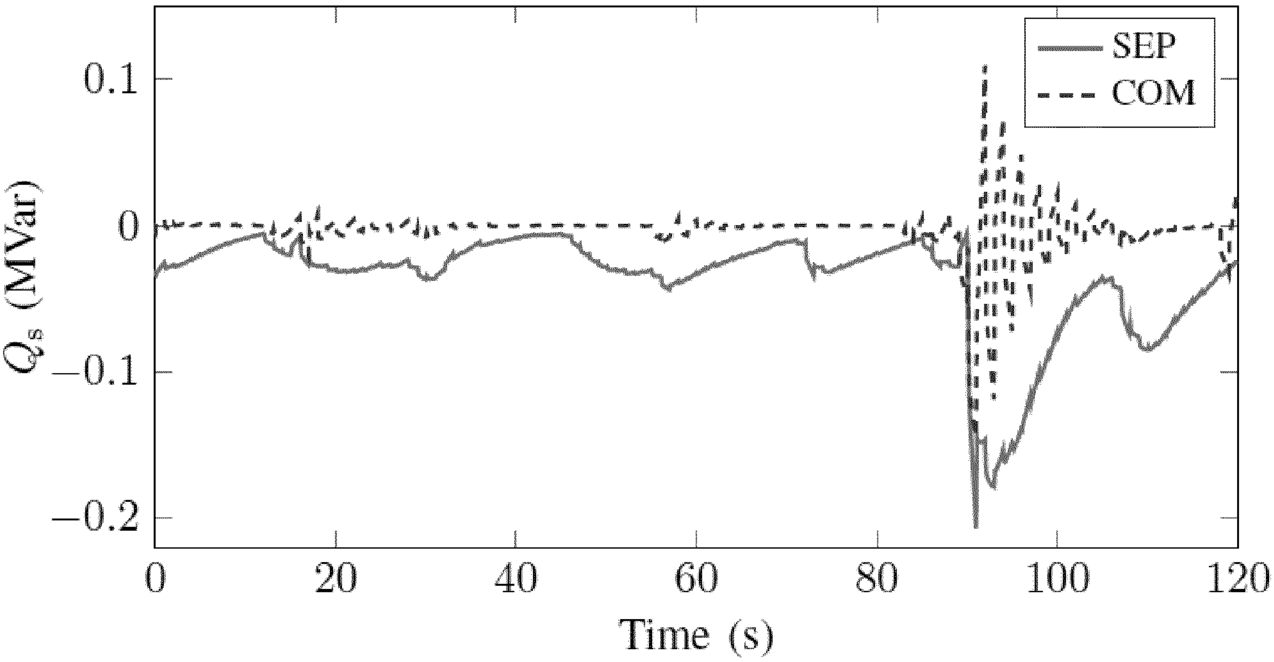

SEP
COM
0.1
0
−0.1
−0.2
Q_s (MVar)
0
20
40
60
80
100
120
Time (s)

FIG. 7

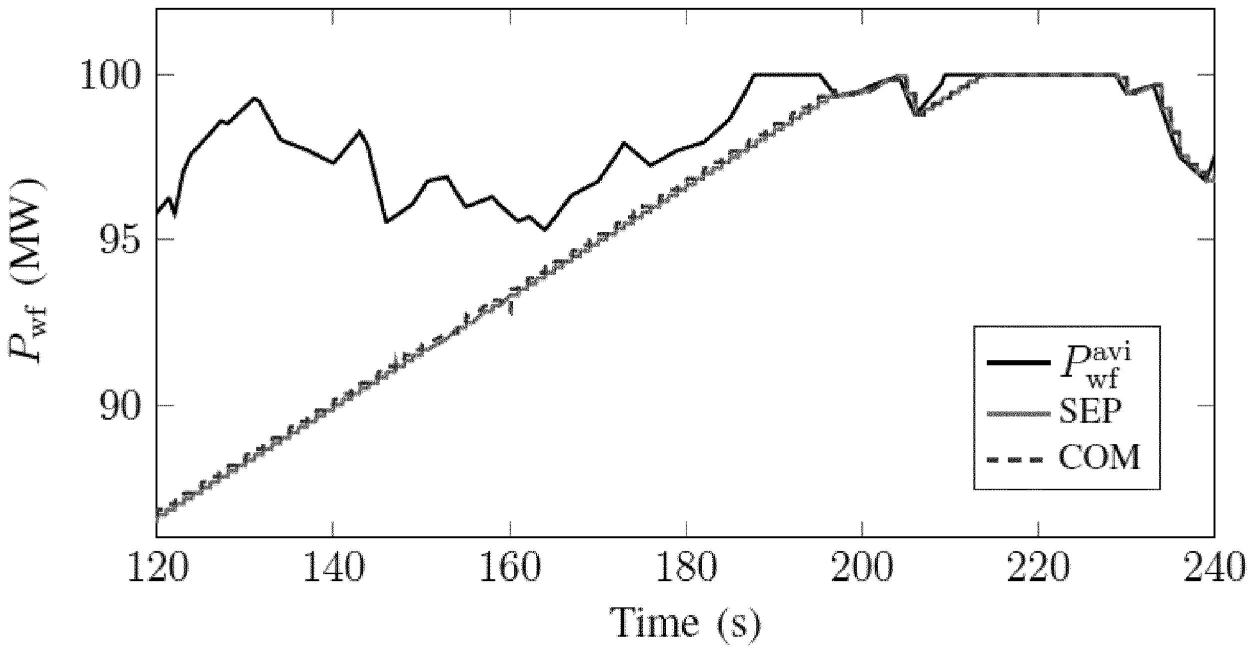
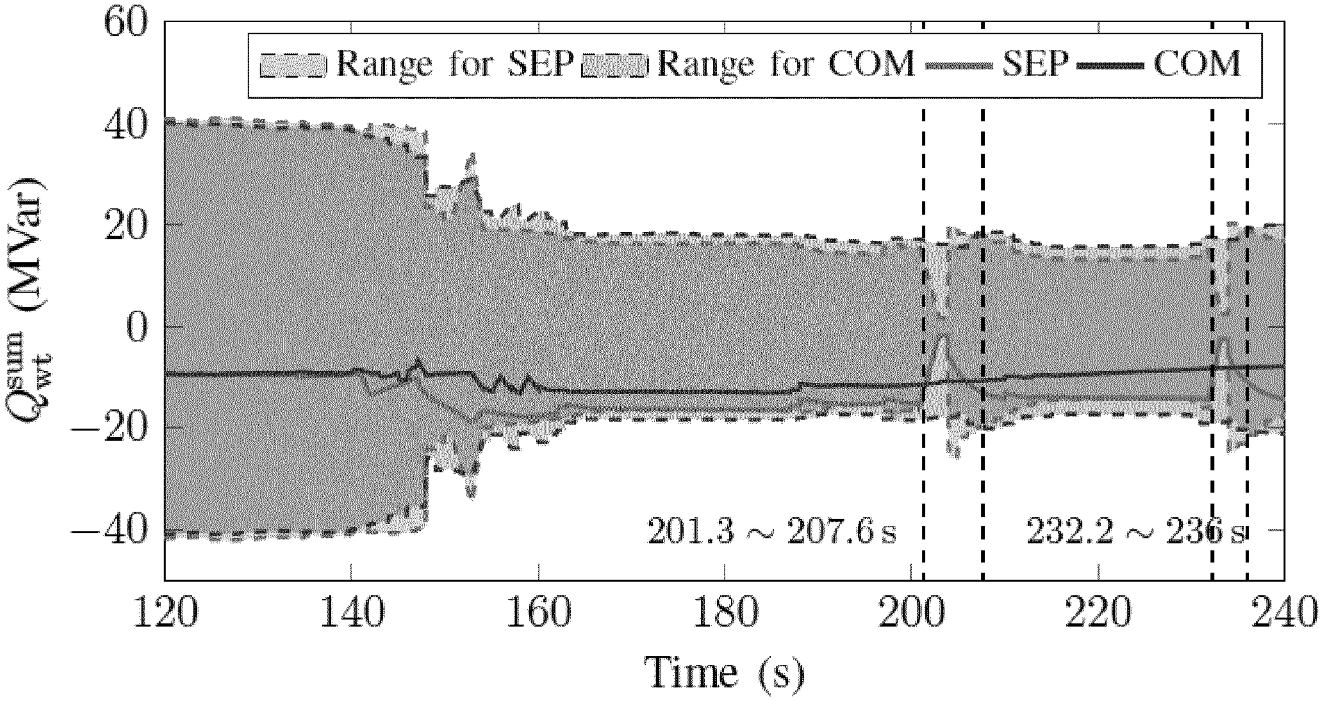
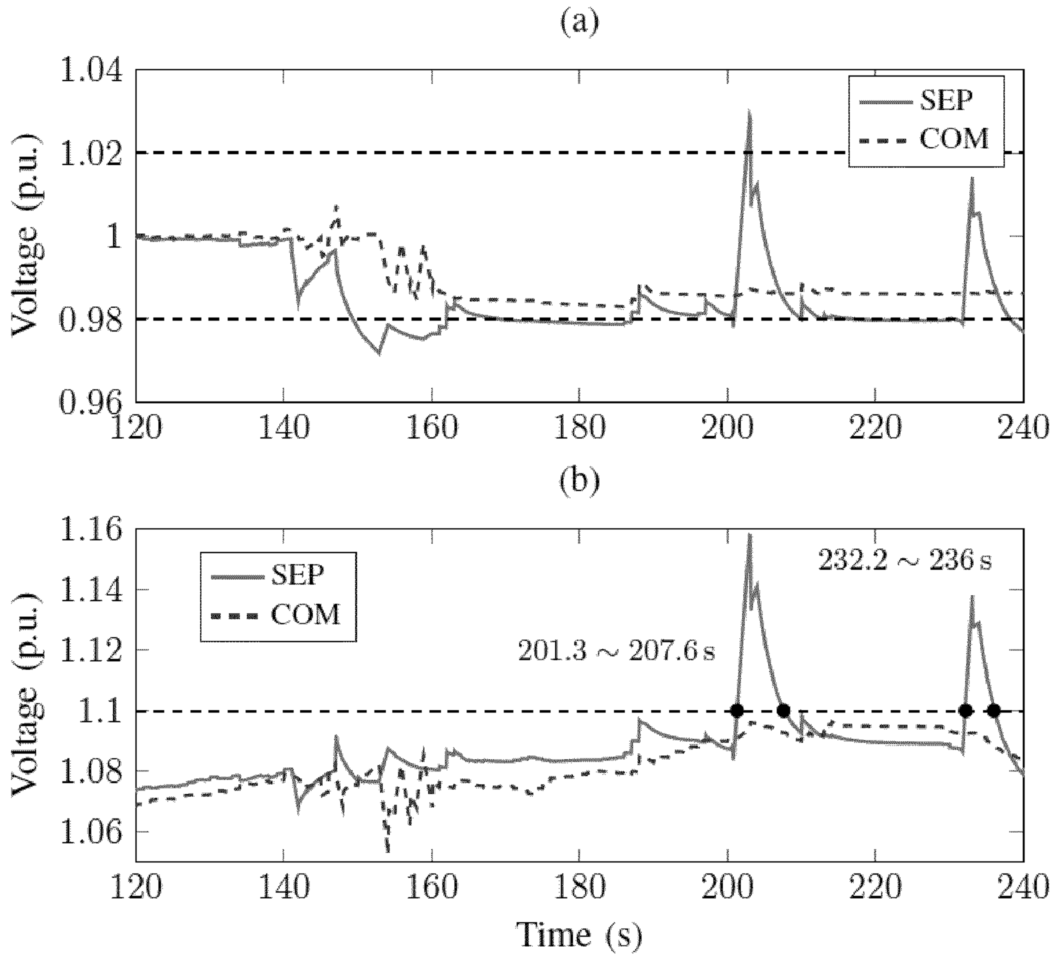

P_{wf}^{avi}
SEP
COM
100
95
90
P_{wf} (MW)
120
140
160
180
200
220
240
Time (s)

FIG. 8



Range for SEP
Range for COM
SEP
COM
Q_{wt}^{sum} (MVar)
60
40
20
0
−20
−40
201.3 ∼ 207.6 s
232.2 ∼ 236 s
120
140
160
180
200
220
240
Time (s)

FIG. 9



(a)
SEP
COM
Voltage (p.u.)
1.04
1.02
1
0.98
0.96
120
140
160
180
200
220
240
(b)
SEP
COM
232.2 ∼ 236 s
201.3 ∼ 207.6 s
Voltage (p.u.)
1.16
1.14
1.12
1.1
1.08
1.06
Time (s)

FIG. 10

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2017/084362

A. CLASSIFICATION OF SUBJECT MATTER
INV. H02J3/38 F03D7/04
ADD. H02J3/18

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H02J F03D

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	CAI YU ET AL: "Model predictive control-based wind farm power control with energy storage", 2014 INTERNATIONAL CONFERENCE ON POWER SYSTEM TECHNOLOGY, IEEE, 22 December 2014 (2014-12-22), pages 2674-2679, XP032712085, DOI: 10.1109/POWERCON.2014.6993658	1,2,4,5, 7,13-17
Y	figure 2 Sections II and III	3,6, 10-12
A		8,9

-/--

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
13 March 2018	20/03/2018

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Jonda, Sven

1

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	ZHAO HAORAN ET AL: "Coordinated Voltage Control of a Wind Farm Based on Model Predictive Control", IEEE TRANSACTIONS ON SUSTAINABLE ENERGY, IEEE, USA, vol. 7, no. 4, 20 April 2016 (2016-04-20), pages 1440-1451, XP011623224, ISSN: 1949-3029, DOI: 10.1109/TSTE.2016.2555398 [retrieved on 2016-09-16]	3,6, 10-12
A	figure 2 Sections II, III and VI -----	8,9
A	US 2014/225370 A1 (MAYER PETER FREDERICK [SG] ET AL) 14 August 2014 (2014-08-14) paragraph [0039] - paragraph [0054] -----	1-15
A	WO 2014/082642 A1 (VESTAS WIND SYS AS [DK]) 5 June 2014 (2014-06-05) figures 4-6 -----	1-15

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2017/084362

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2014225370 A1	14-08-2014	US 2014225370 A1	14-08-2014
		WO 2013044922 A1	04-04-2013
WO 2014082642 A1	05-06-2014	EP 2926002 A1	07-10-2015
		US 2015322921 A1	12-11-2015
		WO 2014082642 A1	05-06-2014